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Gravitational evidence for an undifferentiated **Callisto**

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Before the arrival of the Galileo spacecraft at Jupiter, models for the interior structure of the four galilean satellites- 10. Europa, Ganymede and Callisto--ranged from uniform mixtures of rock --- to and ice (that is, undifferentiated objects) for rocky cores surrounded by a mantle of winter ice[1]. Now it appears that 10 has a large metallic core[2] and that Ganymede is strongly differentiated, most probably into a three-layer structure consisting of a metallic core, a silicate mantle and a deep outer layer of ice]. Direct information on rhe interior strut-!ure of Callisto determined from previous spacecraft fly-bys[4-6] was essentially limited to an estimate of the mean density being intermediate between pure ice anti pure rock. Here we report measurements of Callisto's gravitational field which reveal that, in contrast to 10 and Ganymede, this galilean satellite is most probably a homogeneous object consisting of a solar mixture of 40% compressed icc and 600/0 rock (including iron and iron sulphide). Callisto's undifferentiated state is con. istent with the apparent lack of an intrinsic magnetic field[7], and indicates that the outermost galilean satellite has not experienced a heating phase sufficiently high to separate its rock and metal components from the lighter ices.

Galileo's first encounter with Call isto took place on 4 November 1996, and the gravity signal was detected in the radio Doppler data recorded during the encounter. The data analysis was accomplished by fitting a parametrized orbital model to the radio Doppler data by weighted nonlinear least squares[8-10]. Callisto's external gravitational field was modelled by the standard spherical harmonic representation of the gravitational potential[11]. Because we assumed that the orientation of Callisto's principal axes is known, only two non-zero coefficients (J_2 and C_{22}) were included in the model. All other harmonic coefficients were assumed exactly equal to zero. The two included coefficients measure the contributions to the gravitational potential of the spherical harmonics of degree l and order m for $l = 2$, $m = 0$ and $l = 2$, $m = 2$, respectively. In terms of spherical coordinates fixed in the body of Callisto (radius r, latitude ϕ and longitude λ, where r is the radial distance from the centre of mass and longitude is measured from the Callisto–Jupiter line in an equatorial system defined by Callisto's spin axis), the gravitational potential is

(EDITOR: Be consistent in right and left brackets. Either ( ) or [ ])

$$V = \frac{GM}{r}\left[1 - \frac{1}{2}J_2\left(\frac{R}{r}\right)^2(3\ln^2\phi - 1) + 3C_{22}\left(\frac{R}{r}\right)^2\cos^2\phi\cos 2\lambda\right) \quad (1)$$

sin

(EDITOR: This is sin function, not ln function. sin² φ, not ln² φ)

where G is the gravitational constant and M and R are the mass and radius of Callisto. All other harmonics in the gravitational potential are assumed exactly equal to zero. The closest approach to Callisto occurred at an altitude of 1,136 km, at $\phi = 13.195$ and $\lambda = 77.917°$ (west longitude).

(EDITOR: This is redundant. It also appears 10 lines above the equation)

The determination of GM is biased because of a high correlation with Callisto's ephemeris. We are unable to improve on the value (81 ± 3 $km^3 s^{-2}$) determined from Pioneer and Voyager

(EDITOR: This is reference 6, not 16)

encounters[16]. The remaining two gravity coefficients J_2 and C_{22} are not highly correlated with other parameters in the model, but they are highly correlated with each other, so we impose the *a priori* hydrostatic constraint that J_2 is exactly 10/3 of C_{22}. The values that produce the best fit to the encounter Doppler data are $J_2 = (47.7 \pm 11.5) \times 10^{-6}$ and $C_{22} = (14.3 \pm 3.2) \times 10^{-6}$. The Doppler signal generated by these values is shown in Fig. 1. After the fit, the correlation coefficient between J_2 and C_{22} is $\mu = 0.9128$. It may appear from Fig. 1 that the signal-to-noise ratio is not good enough to infer an unambiguous measurement of C_{22}. To the contrary, the data analysis, including an assessment of the co-variance matrix from the nonlinear least squares process, leads us to conclude that the errors on the two parameters represent a best estimate of realistic standard error (essentially a 22% accuracy for the second-degree external gravitational field).

(EDITOR: Replace the clause in question by the following

Because a homogeneous Callisto is unlikely to have high rigidity, the assumption of hydrostatic equilibrium is plausible. However, ~~unlike Ganymede with its two encounters[3] with Galileo (AUTHOR OK)~~, we are not able to place experimental limits on the hydrostatic assumption. In comparison, the value of C_{22} for the Moon (which is clearly non-hydrostatic) is comparable to what would be expected for a highly differentiated Callisto, while the Moon's appropriately scaled J_2 is somewhat larger than what we have measured for a homogeneous Callisto[12]. If Callisto's measured J_2 and C_{22} were significantly less than what we have found, it could indeed be the result of rigidity lowering the values from their hydrostatic homogeneous values. But we have measured an extreme upper limit to J_2 and C_{22}. Rigidity could hide some degree of differentiation in Callisto if its present distortion is a fossil tidal/rotational bulge from a time in Callisto's history when it was rotating more rapidly. However, it is unlikely that Callisto could ever have rotated fast enough to offset the effect of significant mass concentration toward its centre. It is also difficult to explain how, once Callisto differentiated, its ice mantle or rock core could become rigid enough to preserve the excess fossil bulge of a rapidly spinning Callisto over geological time. For purposes of interior modelling we therefore assume that the measured J_2 and C_{22} reflect a tidal and rotational distortion of Callisto into a fluid equilibrium figure with the present rotation rate of the satellite.

unlike our previous results from the Galileo Space-craft's two encounters with Ganymede[3],

The theory of equilibrium figures for synchronously rotating satellites is well known[12-15], and we have applied it previously to Io and Ganymede[2,3]. By applying the same theory to Callisto, we find that the measured value of C_{22} implies an axial moment of inertia C, normalized to MR^2, of $C/MR^2 = 0.406$, with 1σ lower bound of 0.367. The axial moment of inertia provides a direct constraint on the internal mass distribution[16,17]. For a uniform-density body, $C/MR^2 = 0.4$. The smaller the value of C/MR^2, the more concentrated is the body's mass towards its centre. The determined value of C/MR^2 for Callisto clearly indicates a body of uniform density. Even the 1σ lower bound implies a nearly homogeneous body, given the mean density and radius of Callisto (Fig. 2). An outer ice layer can be at most ~300 km thick for $C/MR^2 = 0.367$. But for these models the interior density is between about 1,900 and 2,200 kg m^{-3} (Fig. 2), indicating that the interior would still contain a large fraction of ice, and Callisto's rock/metal and ice would be only partially separated. Apparently, Callisto was never heated enough to substantially separate its ice and rock/metal components to form a liquid metallic core, and generate a magnetic field by dynamo action, as Ganymede has done[18]. Callisto is only slightly smaller and less massive than Ganymede, hence accretional and radiogenic energy sources would have heated Callisto only slightly (AUTHOR: OK?) less than Ganymede[1]. Ganymede might have received a tidal frictional heat pulse in the past, passing through a resonance with Io and Europa[19], that was large enough to cause a core diferentiation and/or initiate core dynamo action. Callisto would not have experienced such tidal heating and, accordingly, Callisto's failure to differentiate may be attributed to its orbital dynamical isolation as the galilean satellite

yes

farthest from Jupiter. [ ]

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(EDITOR: Program, not programs)

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(AU1'110R: refs1–6 reordered its editing: please check **renumbering**)

OK, except for 6, not 16 at top of p. 2.

(SUB-EDITOR: UPDATE REF 7, INCLUDING TITLE CHECK)

(AUTHOR; IN ref. 8 please give title of Tech Rep.)

title: → Orbit Determination Program

DISPLAYITEMS: FIG. 1 B/W; FIG. 2 B/W; TABLES O; GALLEY '<0: 287

Figure 1 Best fit **second-degree** gravity **signal** (J_2 = **47.7 x 10^{-6} and** [illegible] = 14.3 × 10^{-6}) detected in the radio Doppler data from Galileo at Callisto encounter. The Doppler velocity is defined by $c\Delta\nu/\nu$, **where** $\Delta\nu$ is the **Doppler** frequency shift referenced to the spacecraft's crystal oscillator, ν is the transmitted frequency ~2.3 GHz and c is the **speed** of light. During encounter, the data were recorded by NASA's Deep Space Network tracking facility in Spain. **Doppler** residuals with respect to the best-fit gravity **model** are indicated by filled circles. Their standard error is ~0.73 mm **s**$^{-1}$. Outside the displayed encounter interval, the spacecraft transmission was locked to **a** radio signal from the ground and the standard errors are about a factor of four less. Data included in the fit extend from 30 [illegible] 1996 14:52:30 [illegible] to [illegible]7 h and 39 min after closest approach on 4 November 1996, 14:21:00 [illegible]. **The** gap in the **residuals** centred **around** 30 min [illegible] encounter reflects **a** gap in **the raw** Doppler data. Because of an unknown bias and drift in the spacecraft's crystal oscillator, the encounter data were assigned a standard error of 3 mm s^{-1} (1.8σ) for the error analysis.

(EDITOR: In response to a referee's comment after seeing the revised manuscript, you might add the following sentence at the end of the Fig. 1 caption. But it is not essential, and should not be a note added in proof.)

Any remaining systematic trend in the residuals can be attributed to the propagation of the radio wave through interplanetary plasma.

Figure 2 Two-layer model structures of Callisto consistent with its average density and moment of inertia inferred from the observed C_{22}. Contours of ice thickness in kilometres (solid lines) slope downward to the right; the single [illegible] contour of C/MR^2, representative of the [illegible] lower bound, slopes upward [illegible] [illegible] (AUTHOR OK?) larger than [illegible] even though within a [illegible] of the mean imply a decreasing density with depth and are [illegible]

yes

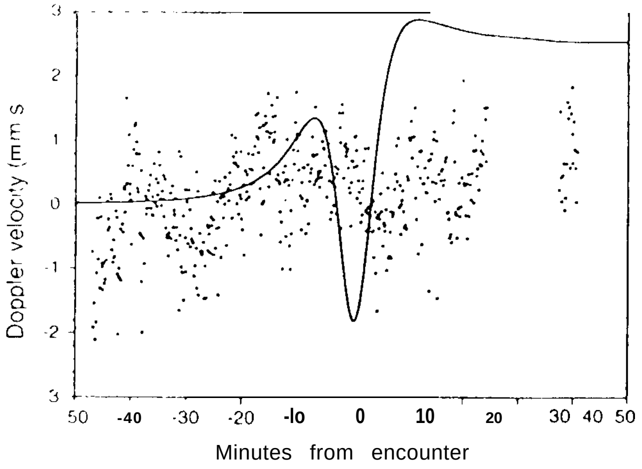

FIGURE N7287F1

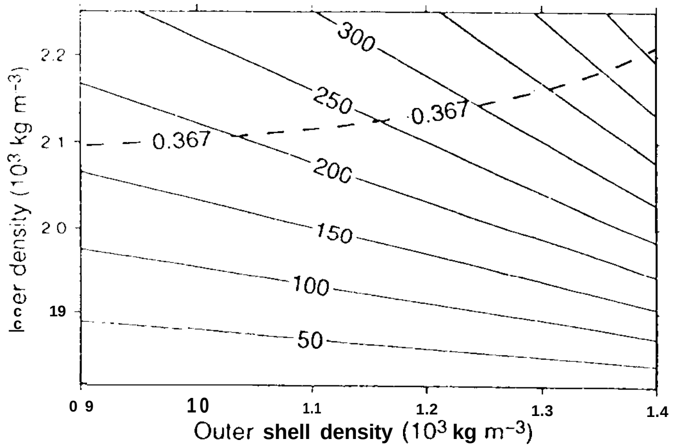

FIGURE N7287F2